Searches for Hidden Sectors and Lepton Number/Flavour Violation in Kaon Decays

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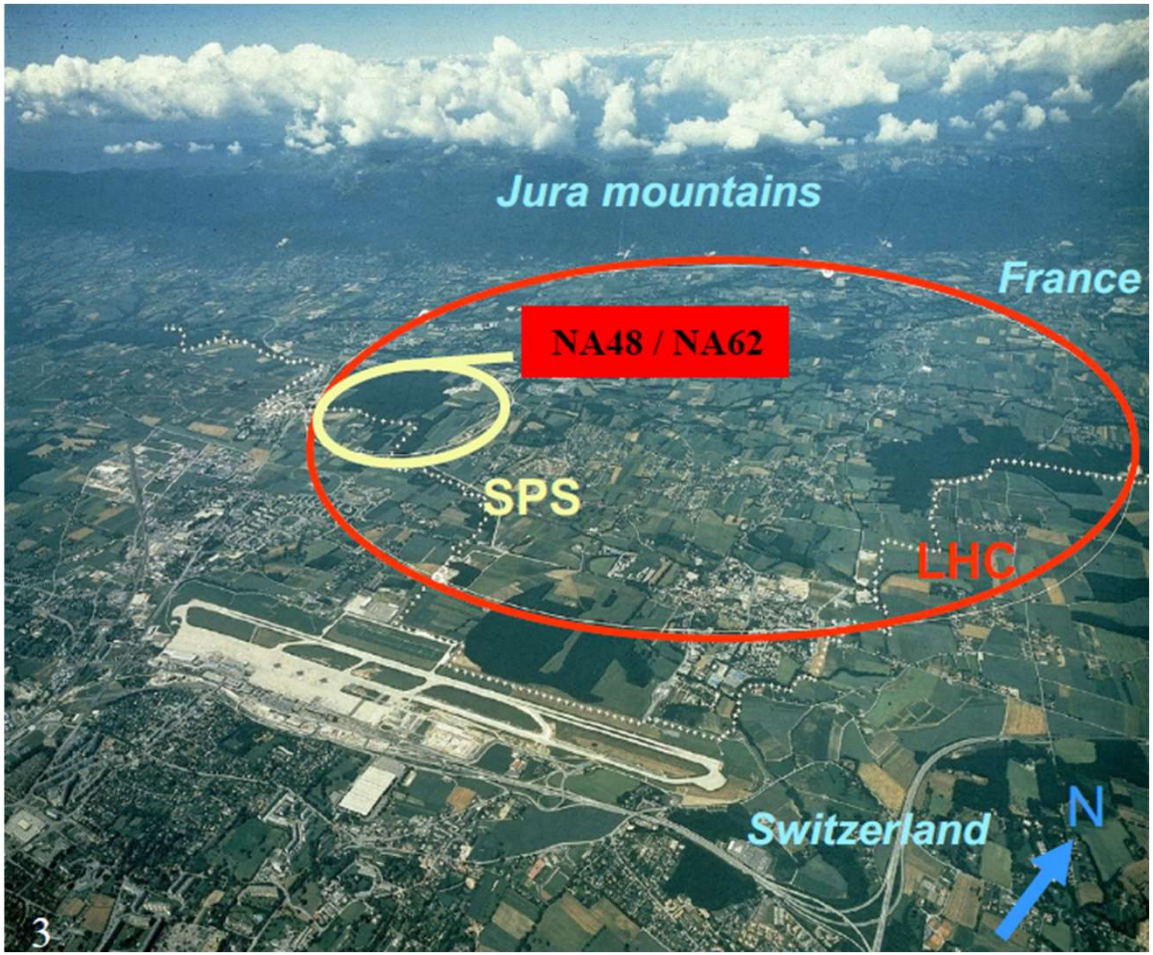
on behalf of the NA62 Collaboration

BLV 2024
October 8th-11th, 2024

Kaon decays at CERN



Earlier: NA31

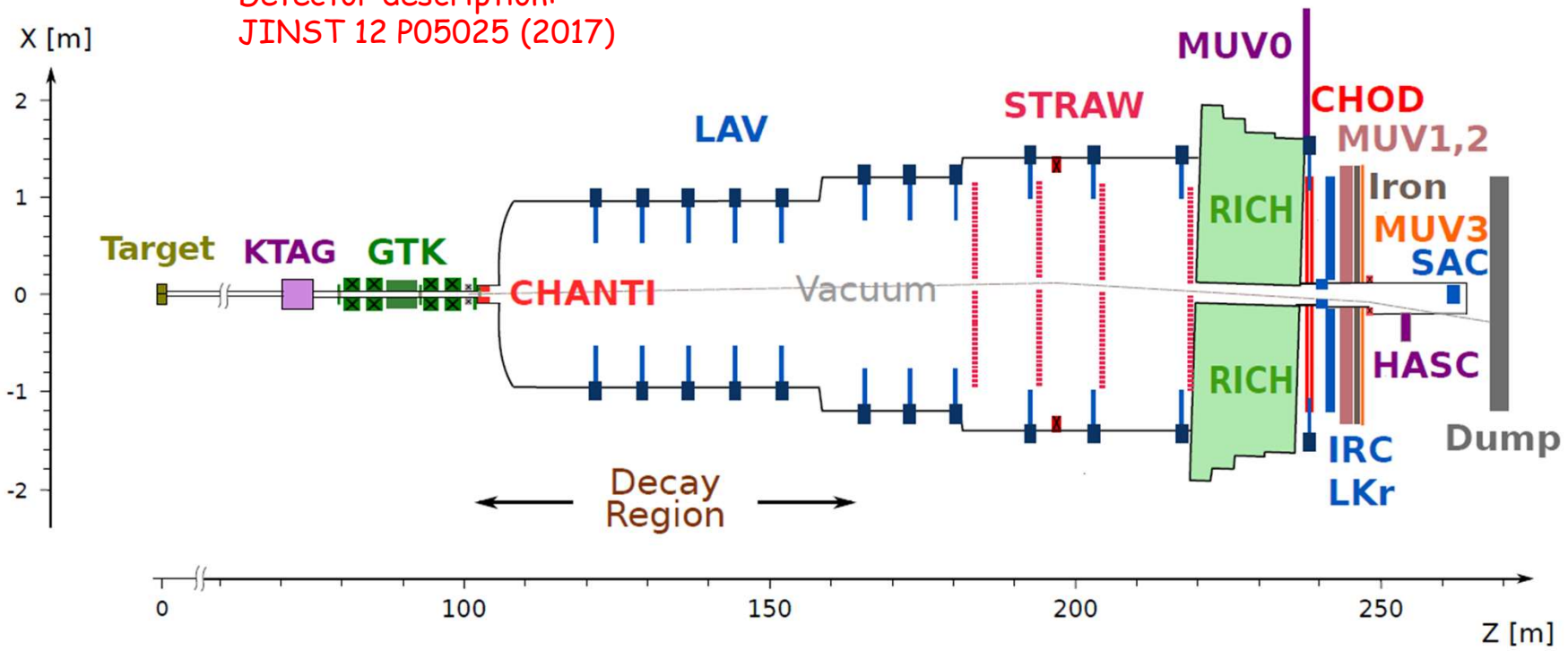
NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
	2003: K^+/K^-	
NA48/2	2004: K^+/K^-	
NA62 R_K phase	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 –18 : $K^+\to\pi^+\nu\nu$ run	
Up to CERN LS3 →	2021 – : $K^+\to\pi^+\nu\nu$ run	

Main NA62 goal: $K^+\to\pi^+\nu\nu$ measurement to 15% precision using the decay-in-flight technique.

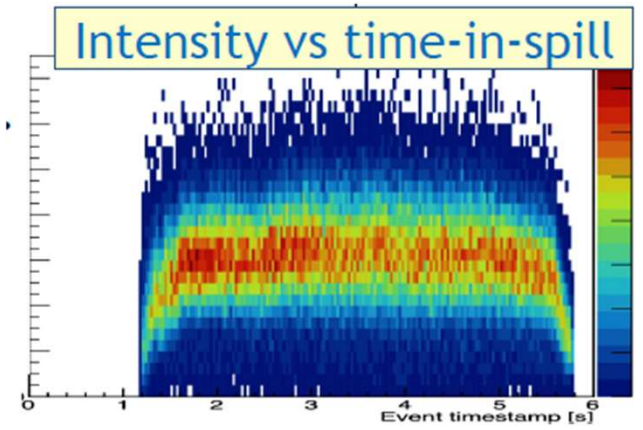
Currently ~300 participants from ~30 institutions.

The NA62 beam

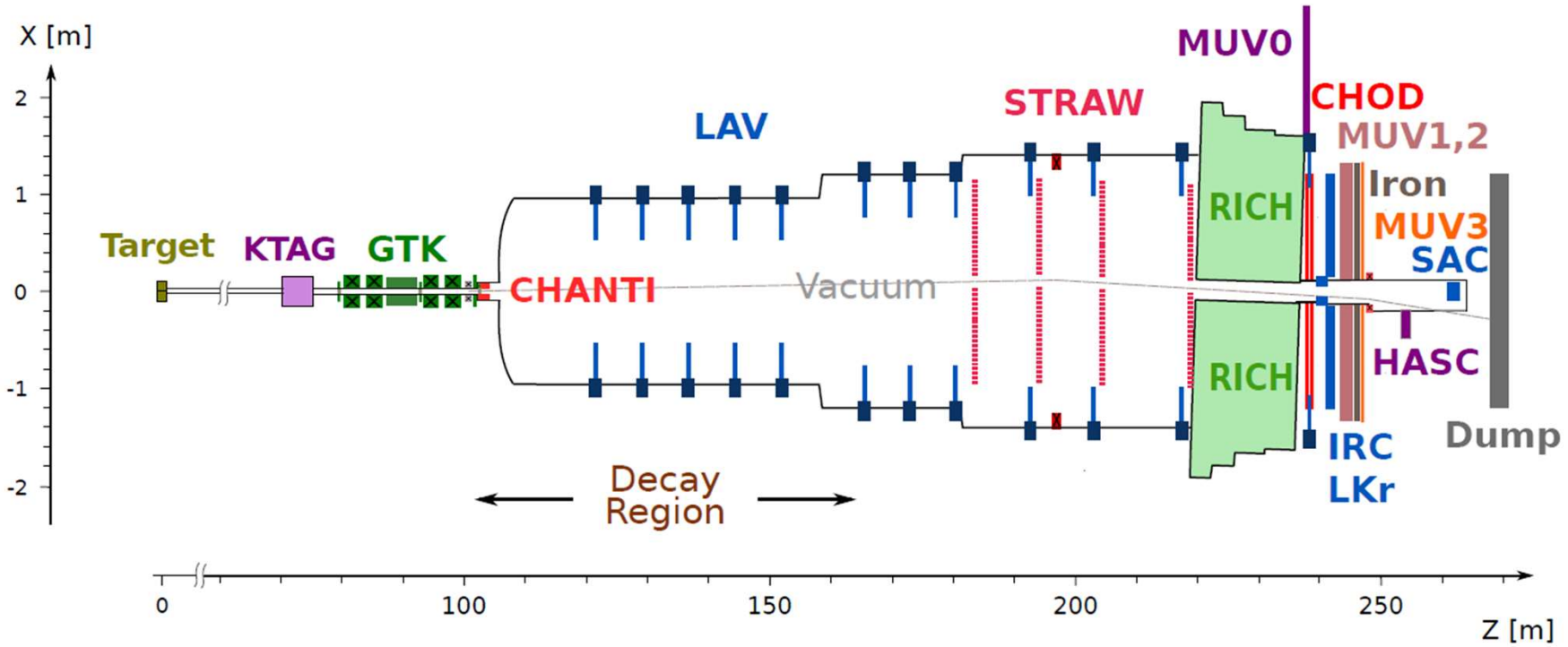
Detector description:
JINST 12 P05025 (2017)



	Beam
Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 μrad
Transverse Size	60 × 30mm^2
Composition	K+ 6%, π+ 70%, p 24%
Nominal Intensity	33 × 10^{11} ppp (750 MHz at GTK3)



The NA62 detector



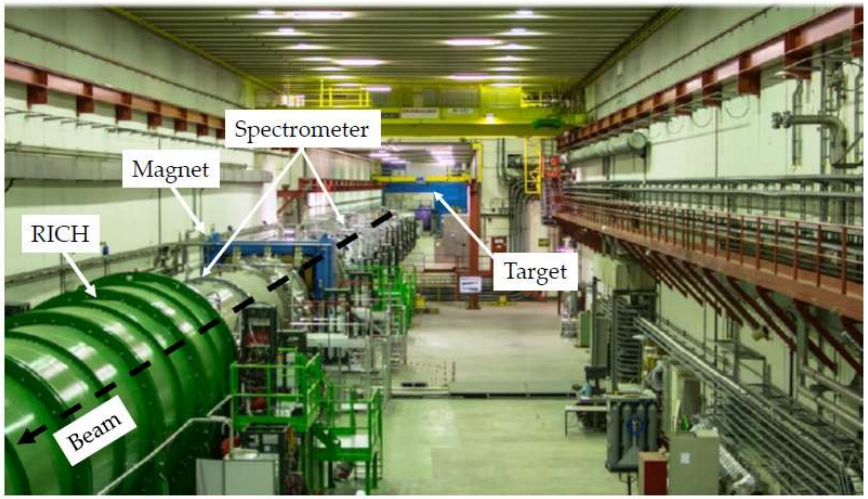
Upstream detectors (K^+)

KTAG	Differential Cherenkov counter for K^+ ID
GTK	Silicon pixel beam tracker
CHANTI	Veto for inelastic beam-GTK3 interactions

Downstream detectors (π^+)

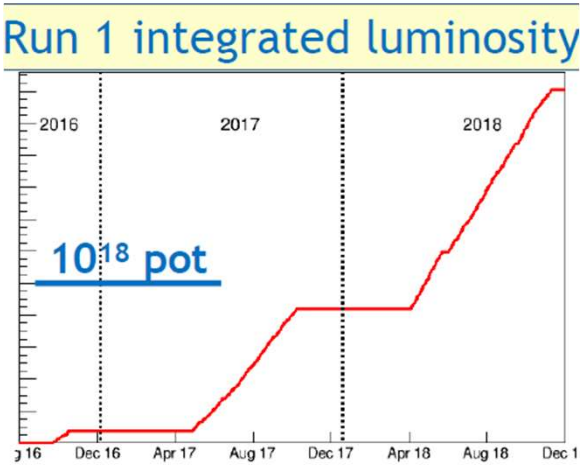
STRAW	Track spectrometer
CHOD	Scintillator hodoscopes
LKr/MUV1/MUV2	Calorimetric system
RICH	Cherenkov for $\pi/\mu/e$ ID
LAV/LKr/IRC/SAC	Photon veto
MUV3	Muon veto

NA62 runs



Run2: 2021-2025, ongoing

Run 1: 2016-2018



Total of 10^{13} useful kaon decays
Average intensity $2*10^{12}$ protons/pulse

- Upgrades wrt Run1:

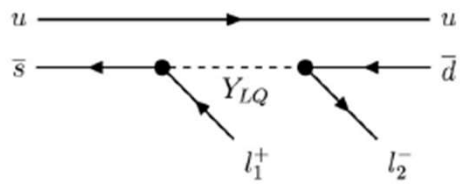
- Added 4th station to GTK beam tracker
- Additional vetoes around beam pipe(both upstream/downstream the FV)
- New veto hodoscope upstream of decay volume (ANTI0)
- New H2-filled Kaon identification detector (CEDAR-H) to reduce material budget [since 2023]
- DAQ stability improved

Searches for LFV/LNV in Kaon decays

Data from Run1

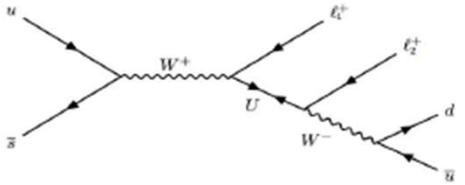
Lepton Flavour Violation: forbidden in SM, predicted by many BSM scenarios

Example: LFV mediated by a leptoquark

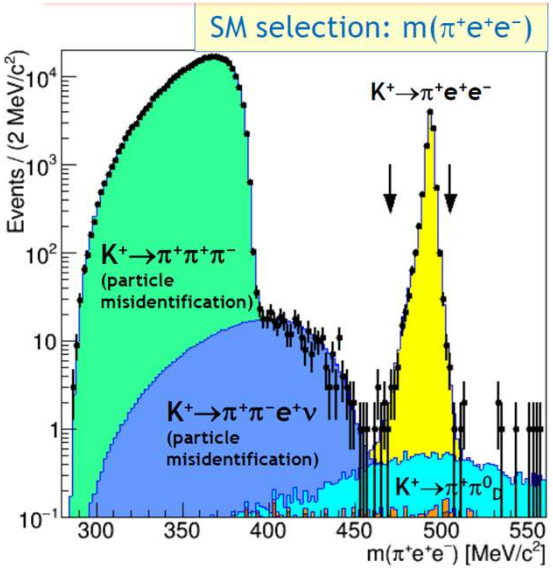


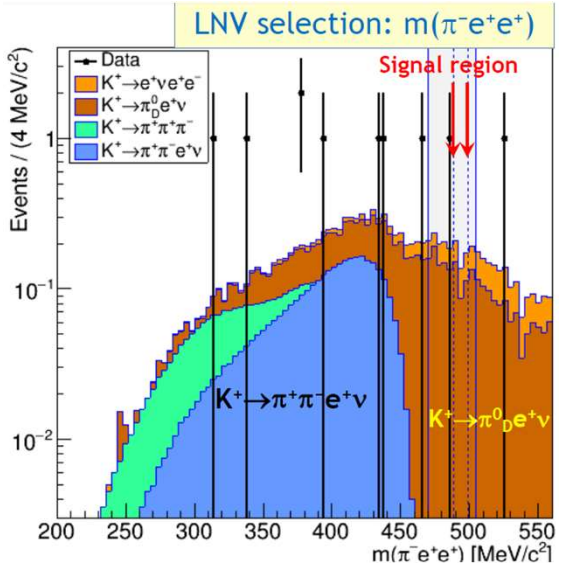
Lepton Number Violation: forbidden in SM, predicted by many BSM scenarios

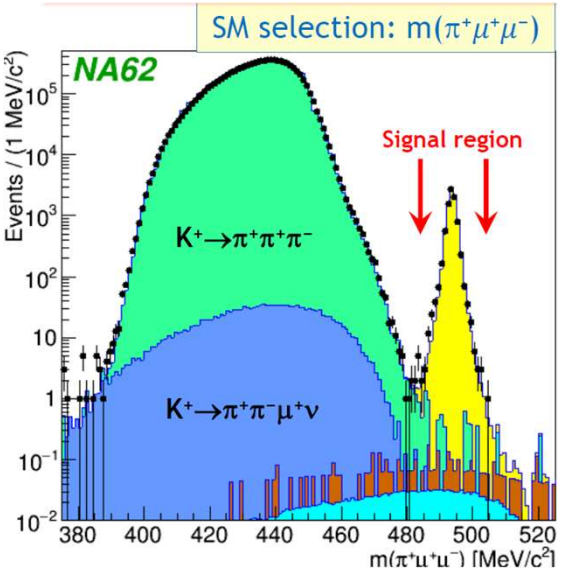
Example: LNV mediated by a Majorana neutrino

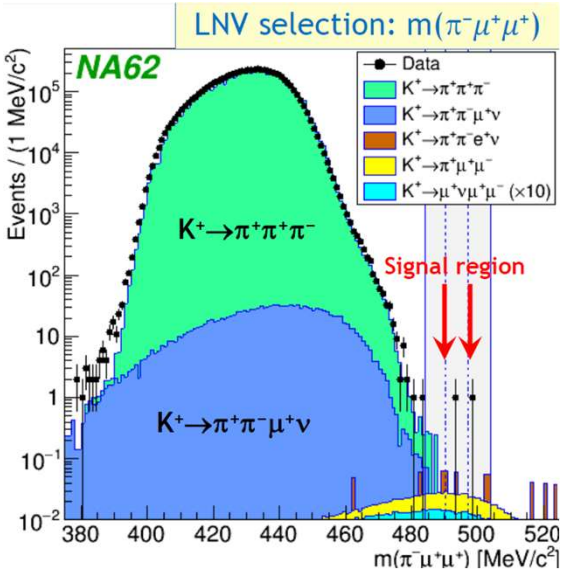


Search for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$









SM selection

Candidates observed: **11041**

BR($K^+ \to \pi^+ e^+ e^-$)=(3.00±0.09)×10^{-7}

K+ decays in FV: **(1.015±0.032)×10^{12}**

LNV selection

Expected background: **0.43±0.09** evt

Candidates observed: **0**

BR($K^+ \to \pi^- e^+ e^+$)<5.3×10^{-11} at 90% CL

PLB830 (2022) 137172

SM selection

Candidates (25% of Run 1 data): **8357**

Background: **0.07%**

BR($K^+ \to \pi^+ \mu^+ \mu^-$)=(0.962±0.025)×10^{-7}

K+ decays in FV: **(7.94±0.23)×10^{11}**

LNV selection

Expected background: **0.91±0.41** evt

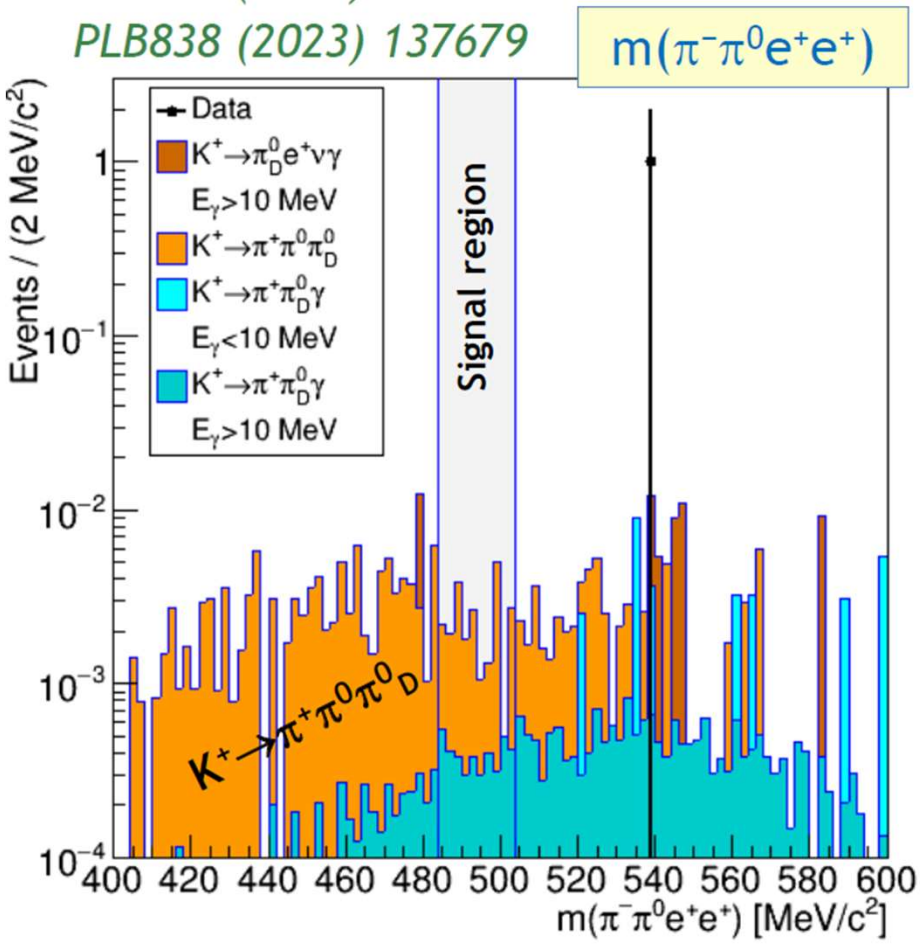
Candidates observed: **1**

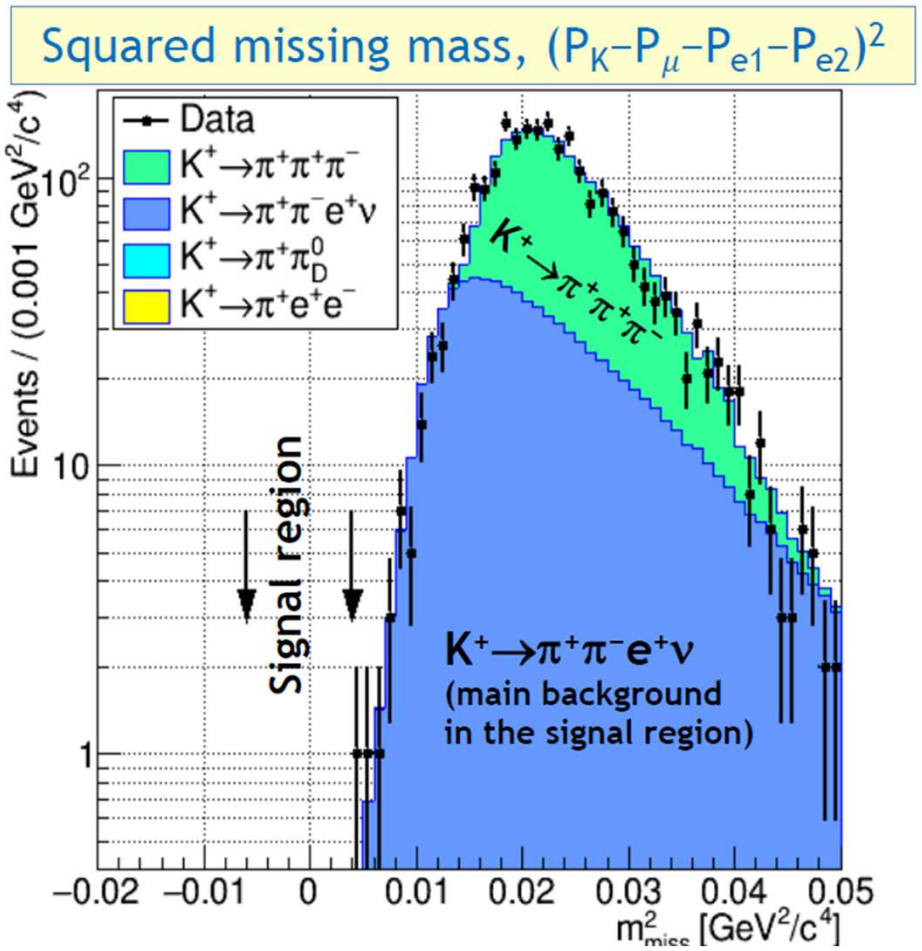
BR($K^+ \to \pi^- \mu^+ \mu^+$)<4.2×10^{-11} at 90% CL

PLB797 (2019) 134794

$K^+ \to \pi^- \pi^0 e^+ e^+$ and $K^+ \to \mu^- \nu e^+ e^+$

PLB830 (2022) 137172
PLB838 (2023) 137679

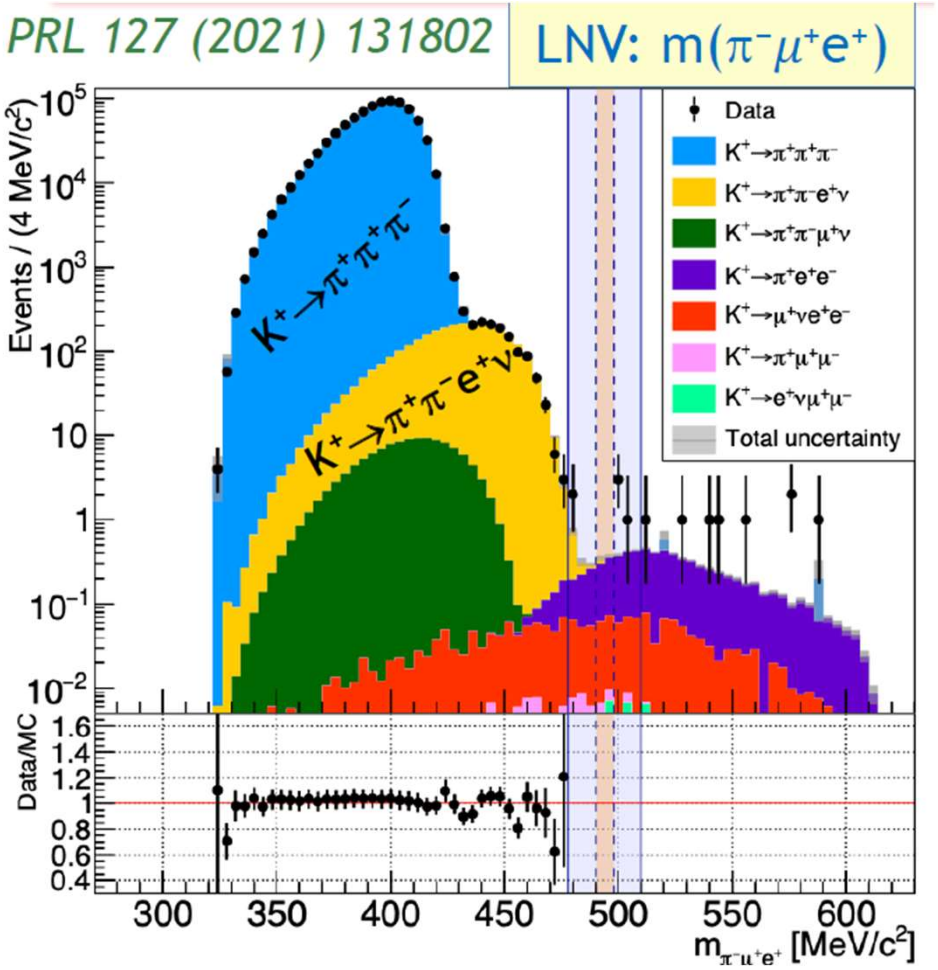


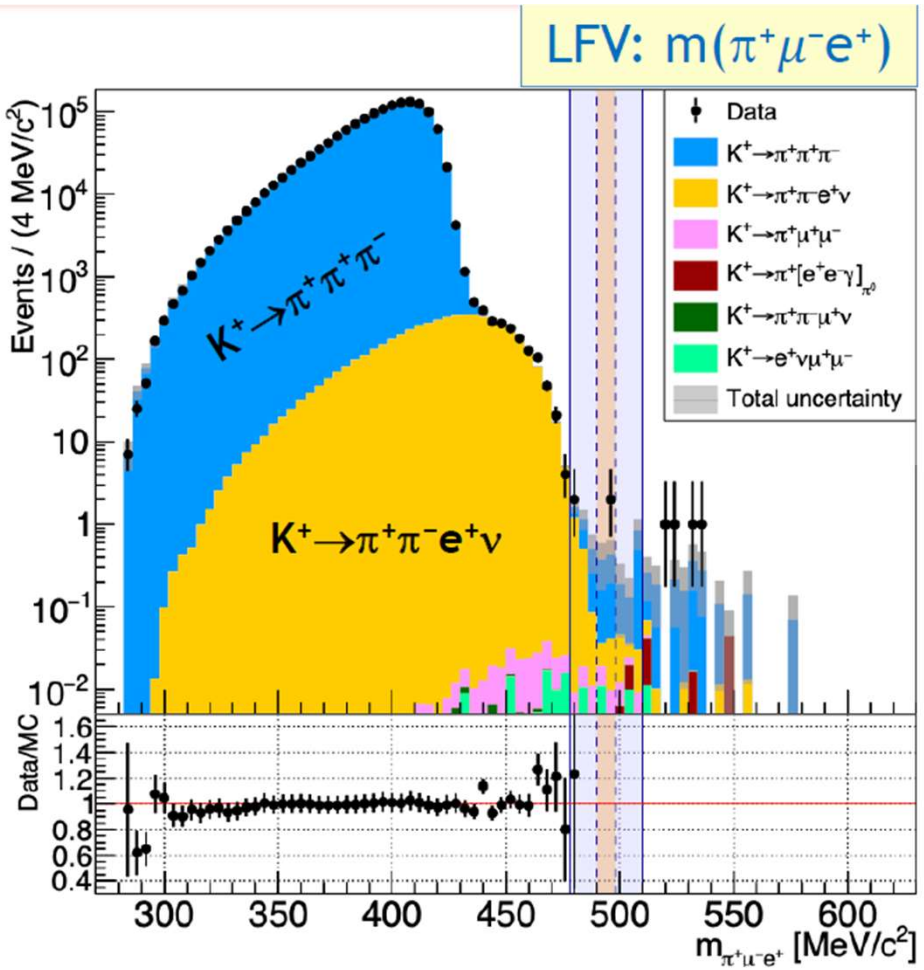


Expected background: **0.044±0.020** evt
Candidates observed: **0**
BR($K^+ \to \pi^- \pi^0 e^+ e^+$)<8.5×10^{-10} at 90% CL

Expected background: **0.26±0.04** evt
Candidates observed: **0**
BR($K^+ \to \mu^- \nu e^+ e^+$)<8.1×10^{-11} at 90% CL

Search for $K^+ \to \pi\mu e$ decays

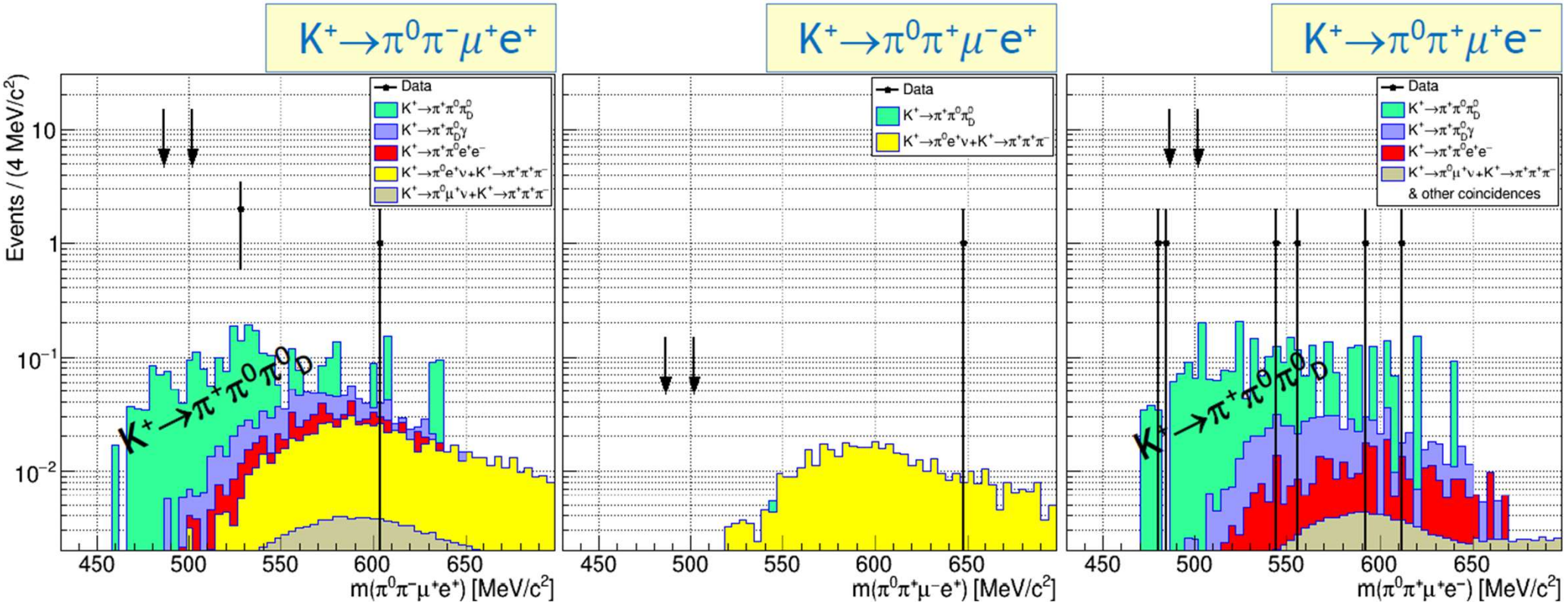




K+ decays in FV: **$(1.33\pm0.02)\times10^{12}$**
Expected background: **1.07±0.20** evt
Candidates observed: **0**
BR($K^+\to\pi^-\mu^+e^+$)<4.2×10^{-11} at 90% CL

Expected background: **0.92±0.34** evt
Candidates observed: **2**
BR($K^+\to\pi^+\mu^-e^+$)<6.6×10^{-11} at 90% CL
BR($\pi^0\to\mu^-e^+$)<3.2×10^{-10} at 90% CL

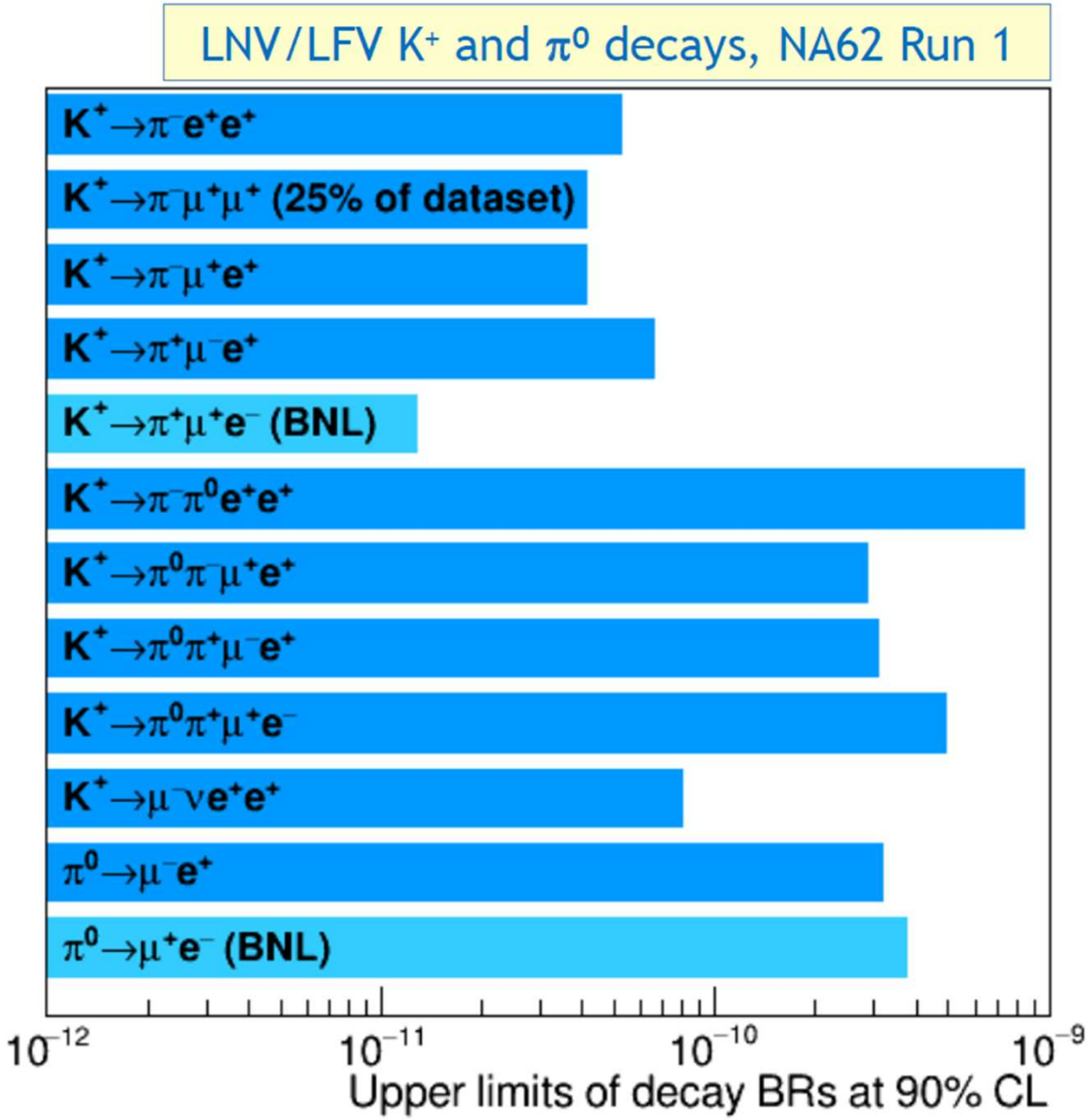
Search for $K^+ \to \pi^0 \pi \mu e$ decays



Mode	Expected Background	Observed candidates	Upper limit of BR at 90% CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33±0.07	0	2.9×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004±0.003	0	3.1×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29±0.07	0	5.0×10^{-10}

To be published

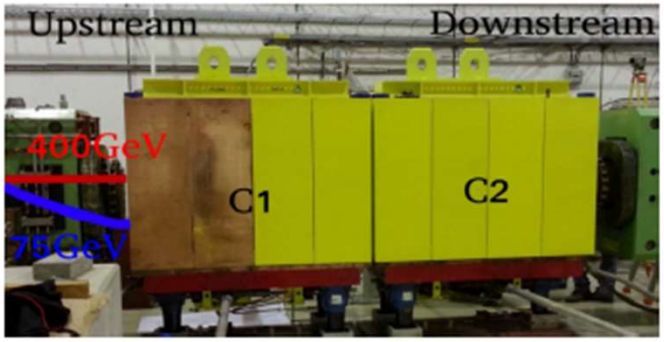
Current status of LFV/LNV decays

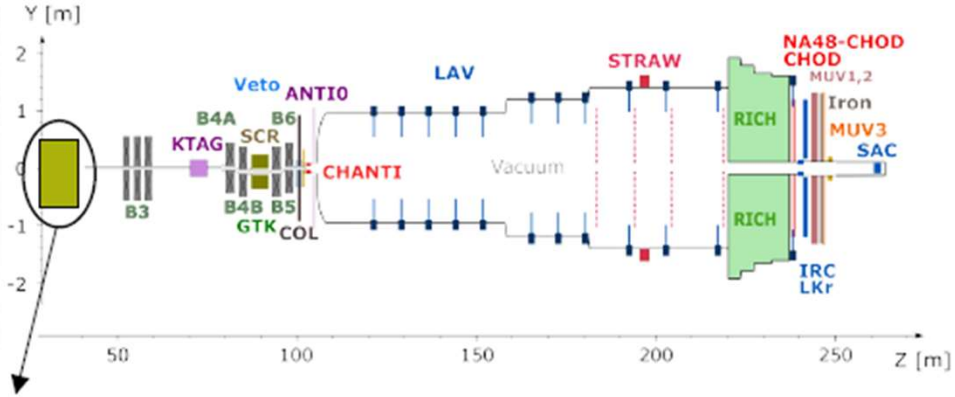


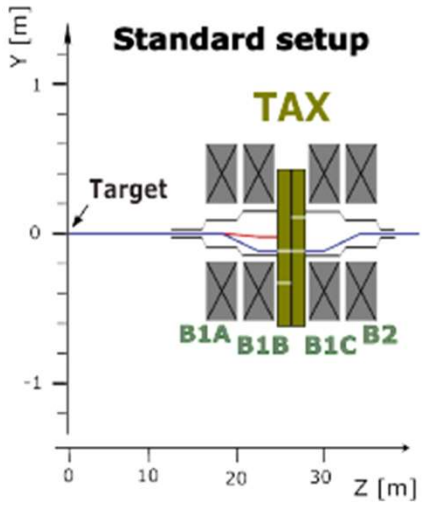
Searches for hidden sectors in Kaon decays

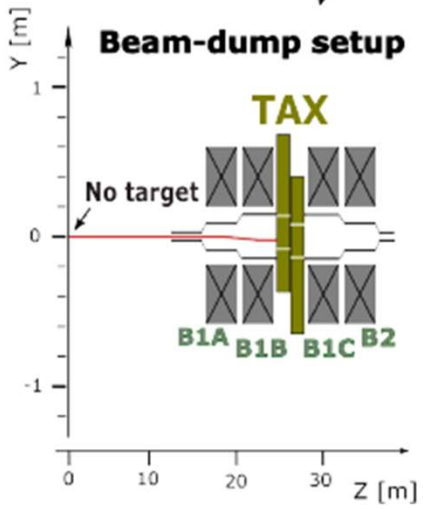
NA62 operation modes for hidden sectors

- Use of specific downscaled trigger masks during $\pi\nu\nu$ runs
- Dedicated runs with the beam in dump mode
  - Target removed, collimator closed, 50% more primary beam intensity









Beam-dump mode:
22 λ_{int} Cu collimator (TAX) closed

1.4×10^{17} protons on target (POT)
collected in dump mode in 2021 (few days)

10^{18} POT (few weeks) to be collected
by end of NA62 data taking (LS3)

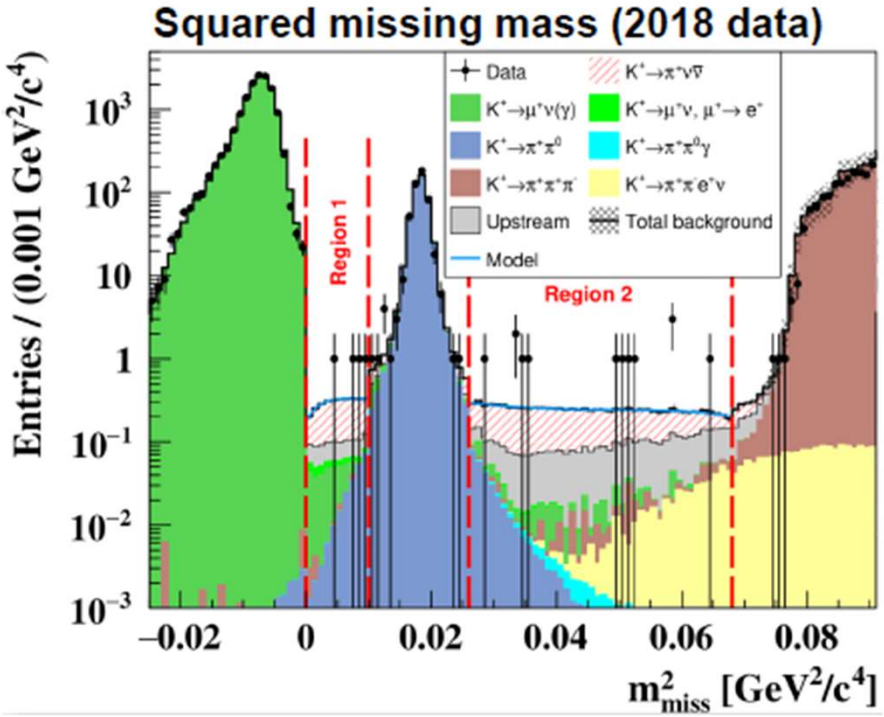
$K^+ \to \pi^+ X_{invisible}$: a $K^+ \to \pi^+ \nu\nu$ spin-off

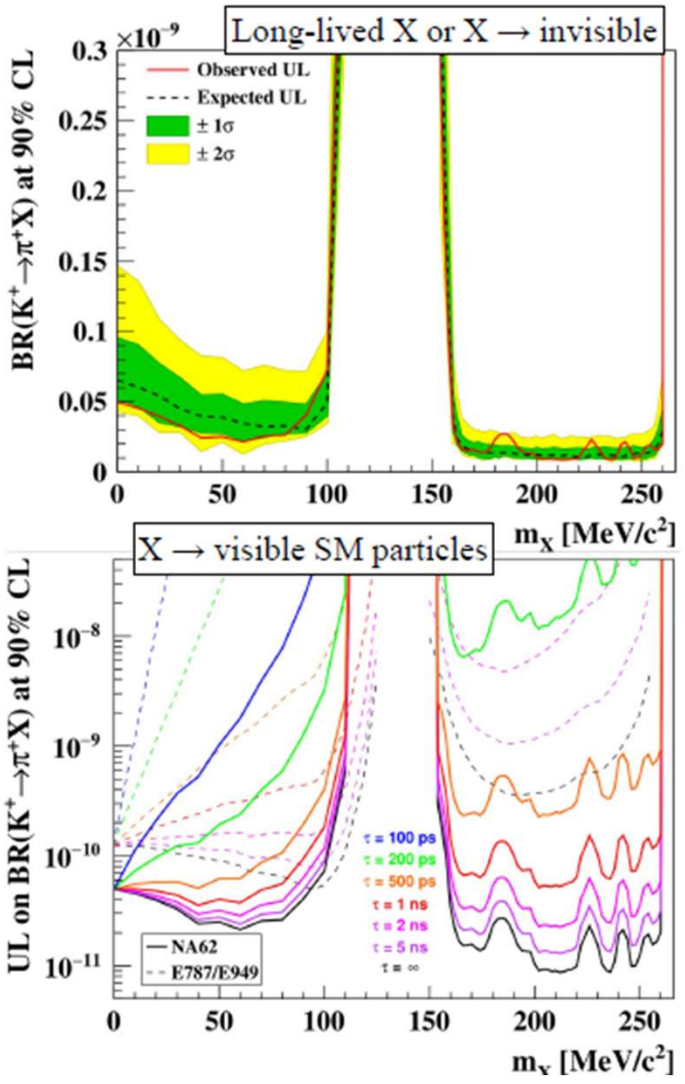
Peak search in the range $0 \leq m_X \leq 110$ MeV/c and $154 \leq m_X \leq 260$ MeV/c

Acceptance scan over m_x and τ_x

Main background from $K^+ \to \pi^+ \nu\nu$

JHEP 06 (2021) 093





$K^+ \to \pi^+ \pi^0_{invisible}$: a $K^+ \to \pi^+ \nu\nu$ spin-off

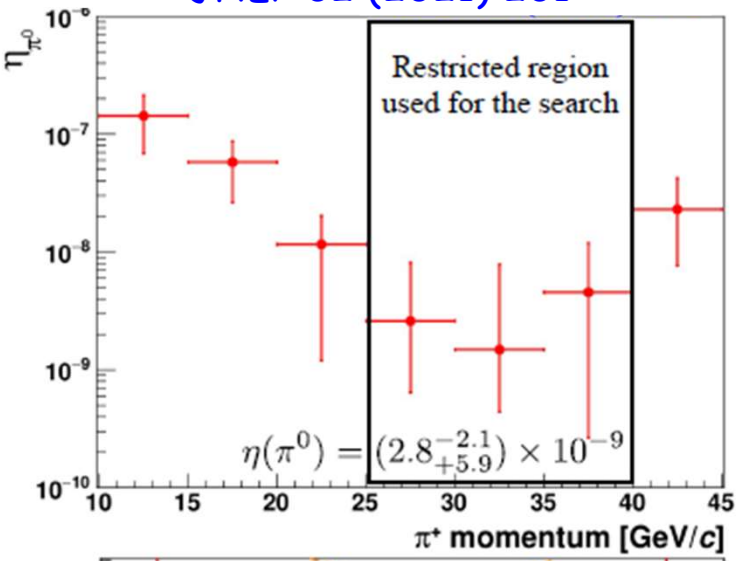
Basic event selection used for $K^+ \to \pi^+ \nu\nu$, but applied to the $K^+ \to \pi^+ \pi^0$ region

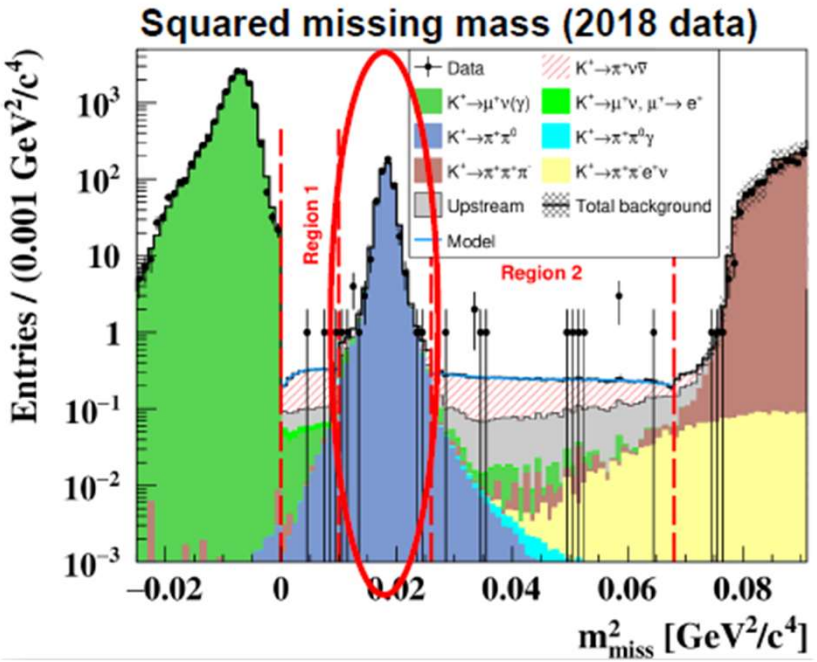
Main background from $K^+ \to \pi^+ \pi^0$ ($\pi^0 \to \gamma\gamma$)
Estimated using MC with single γ efficiency by tag-and-probe method

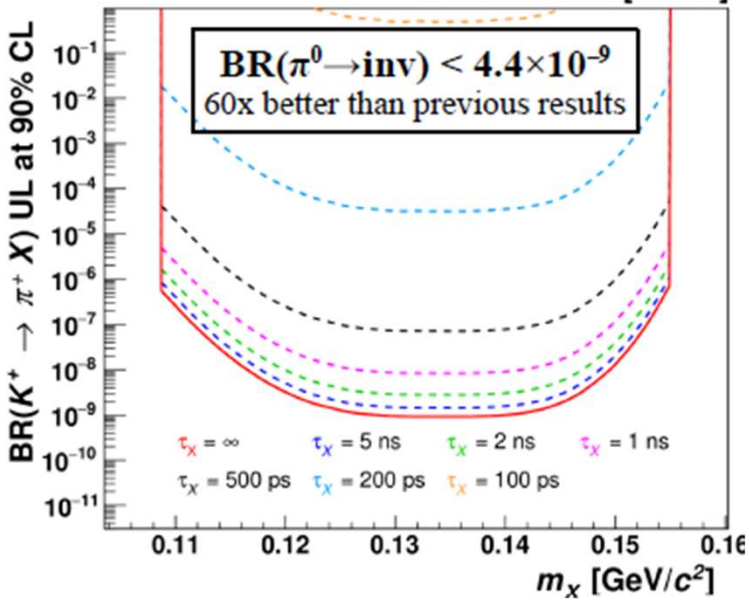
Validates π^0 rejection estimate for $K^+ \to \pi^+ \nu\nu$ analysis

Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8} , observed 12

JHEP 02 (2021) 201







$K^+ \to \pi^+ X(X \to \gamma\gamma)$: a $K^+ \to \pi^+ \gamma\gamma$ spin-off

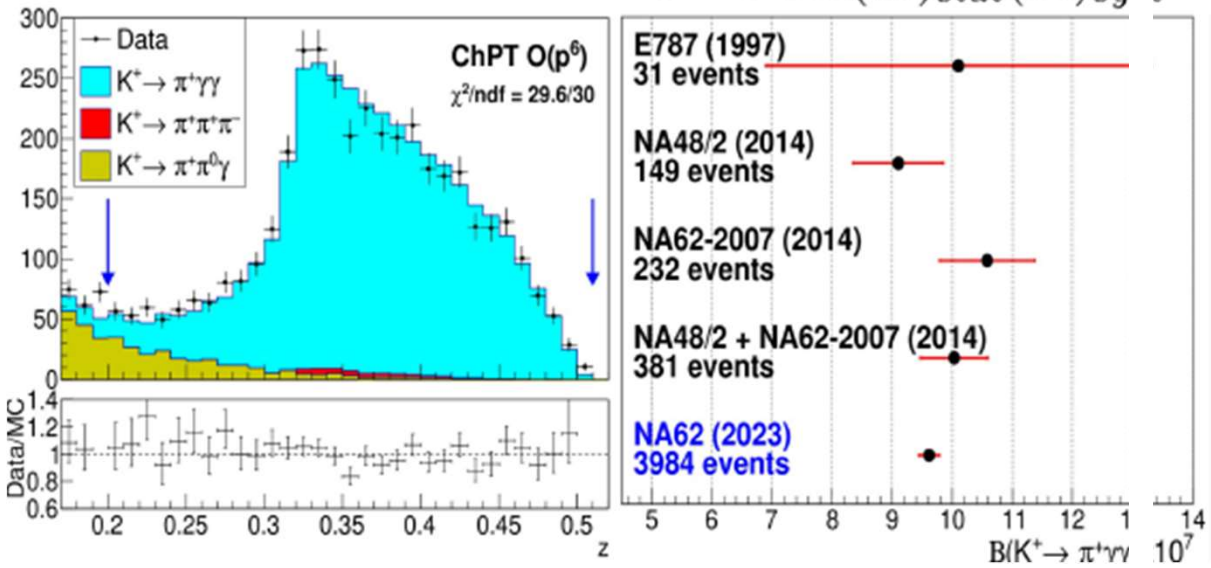
Peak search in the signal region $207 \leq m_X \leq 350$ MeV/c^2

Main background from $K^+ \to \pi^+ \gamma\gamma$

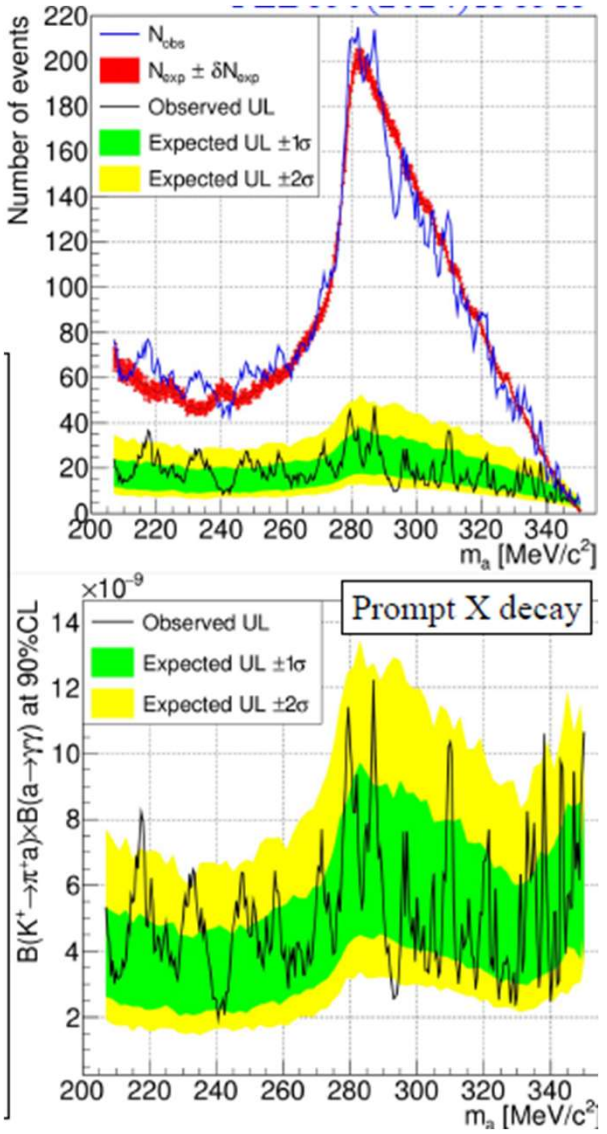
$K^+ \to \pi^+ \gamma\gamma$ analysis

Measurement of the $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$ spectrum to test $O(p^6)$ ChPT

$\hat{c} = 1.144(69)_{stat}(34)_{sy}$ t

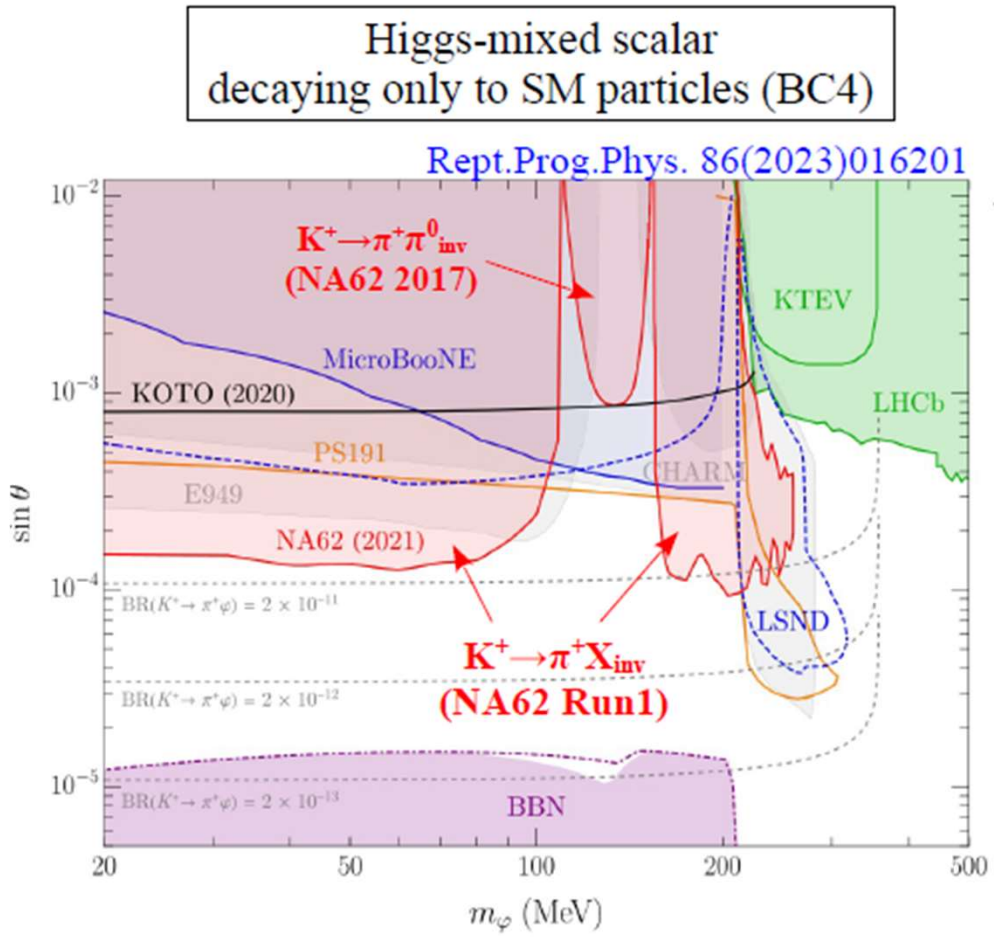


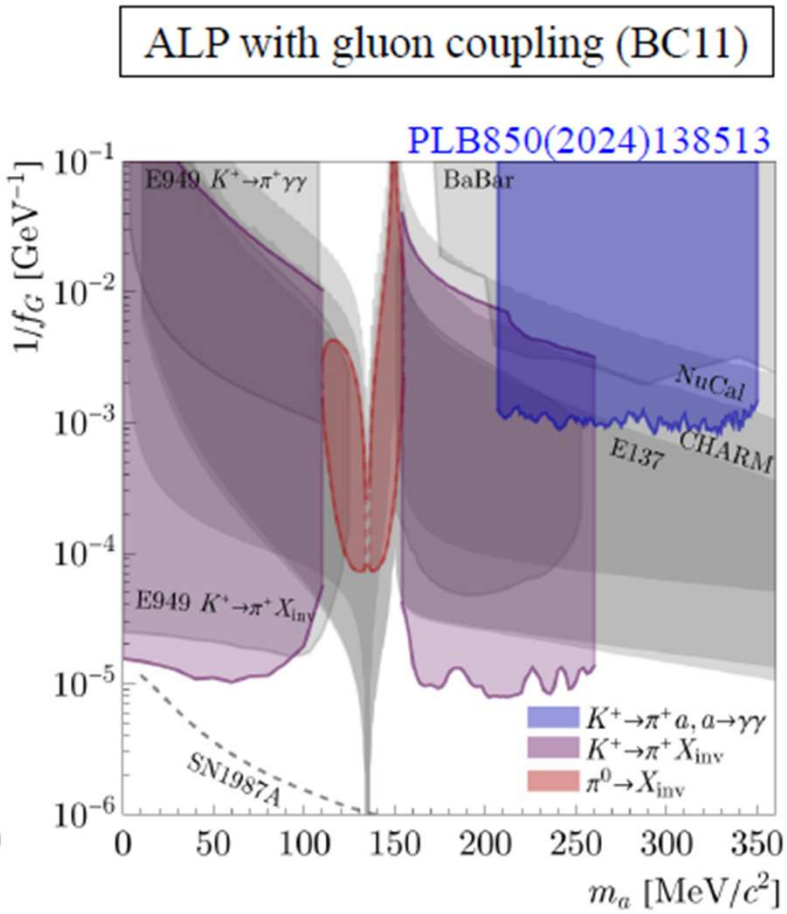
PLB850 (2024) 138513



$K^+ \to \pi^+ X$ searches: interpretation

The limits on the branching ratios of the three above decays translate to the parameter space for hidden-sector portals





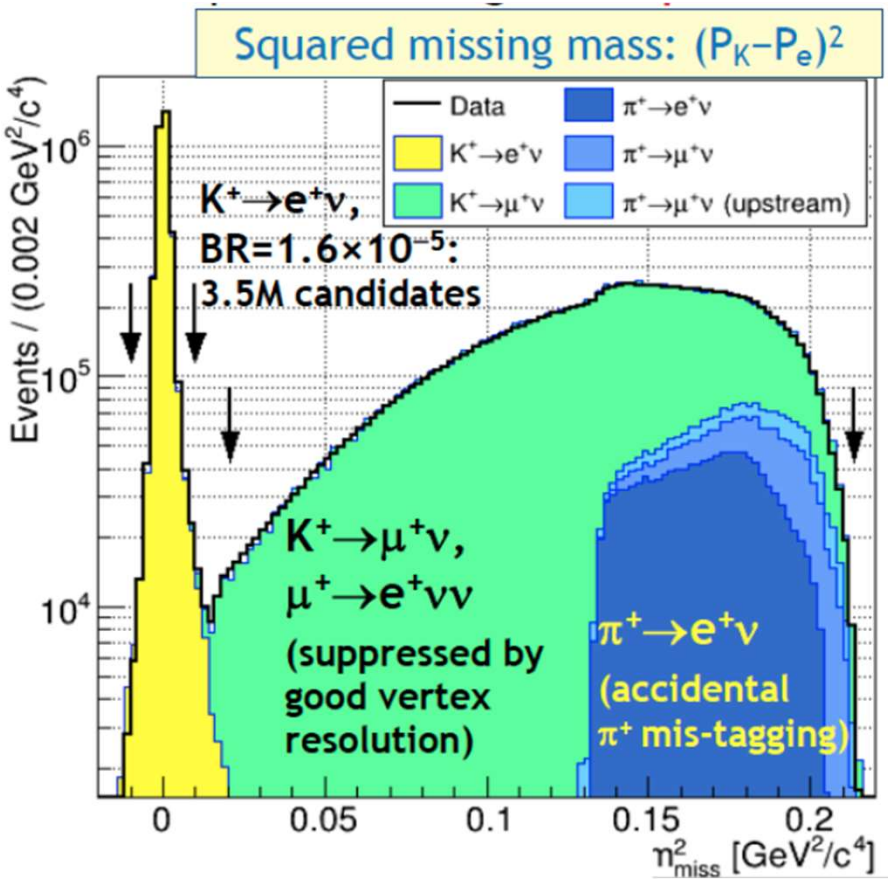
HNL production

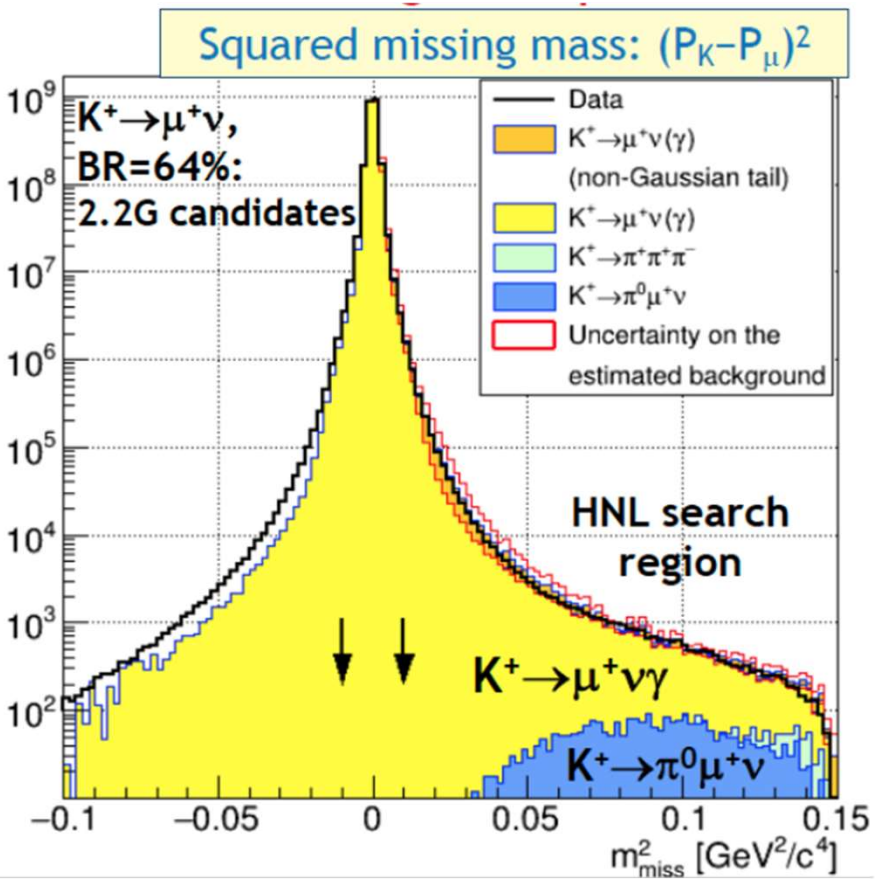
Main Kπνν trigger line used
$N_K = 3.5\times10^{12}$ decays

Single-track selection, with **e+** PID
Peak search in $m^2_{miss} = (P_K - P_e)^2$ distribution corresponding to m_N range 144-462 MeV/c^2
Main background: $K^+\to\mu^+\nu$ ($\mu^+\to e^+\nu\nu$)

Heavily-downscaled (x400) minimum-bias trigger line used $N_K = 4.3\times10^{9}$ decays

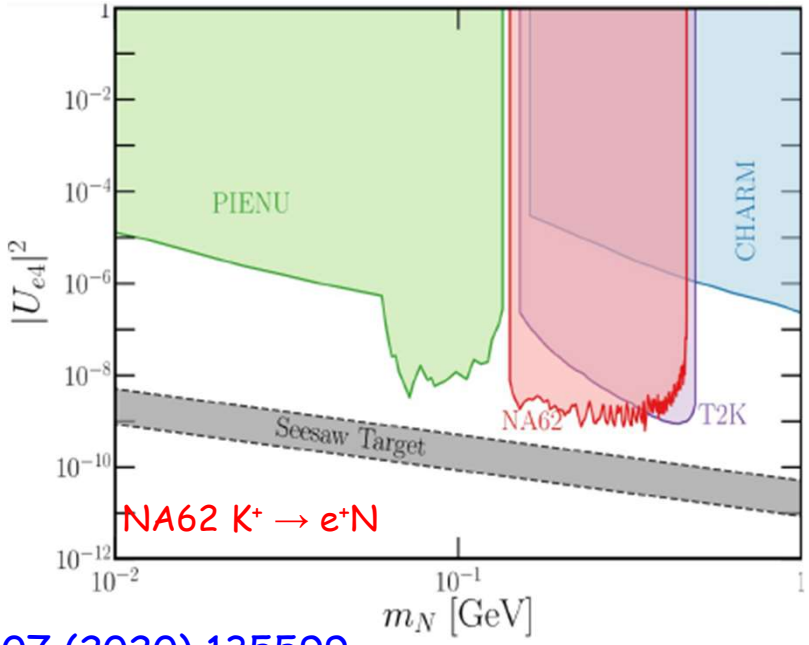
Single-track selection, with **μ+** PID
Peak search in in $m^2_{miss} = (P_K - P_\mu)^2$ distribution corresponding to m_N range 200-384 MeV/c^2
Main background: $K^+\to\mu^+\nu\gamma$



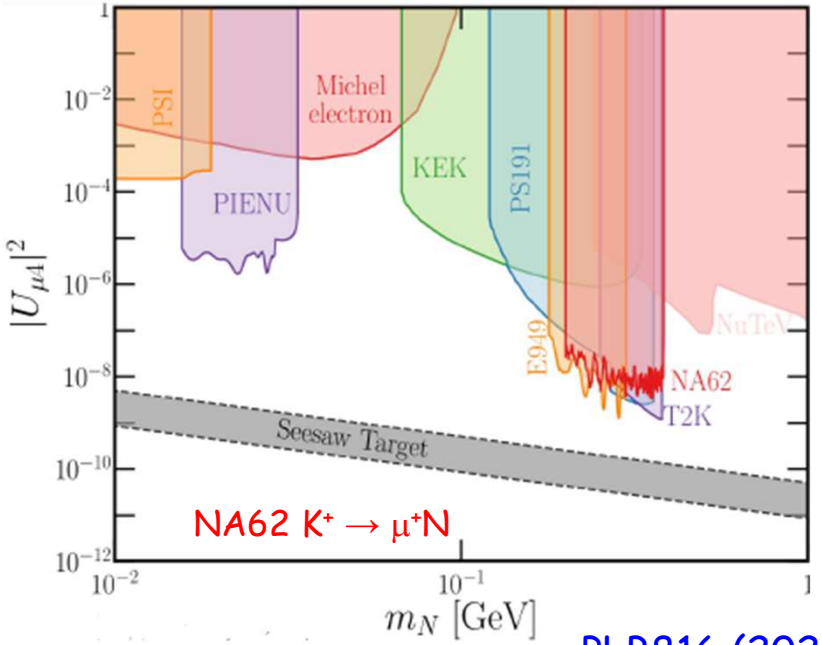


HNL production: results

BC6,7: $|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



PLB807 (2020) 135599



PLB816 (2021) 136259

- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- In both cases, complementary to HNL decay searches at T2K.
- Future pion experiments might reach the seesaw bound.

UL on BR($K^+ \to \mu^+ \nu\nu\nu$) < 1.0×10^{-6} (90%CL) + similar ULs on BR($K^+ \to \mu^+ \nu X_{inv}$) vs m($X_{inv}$)

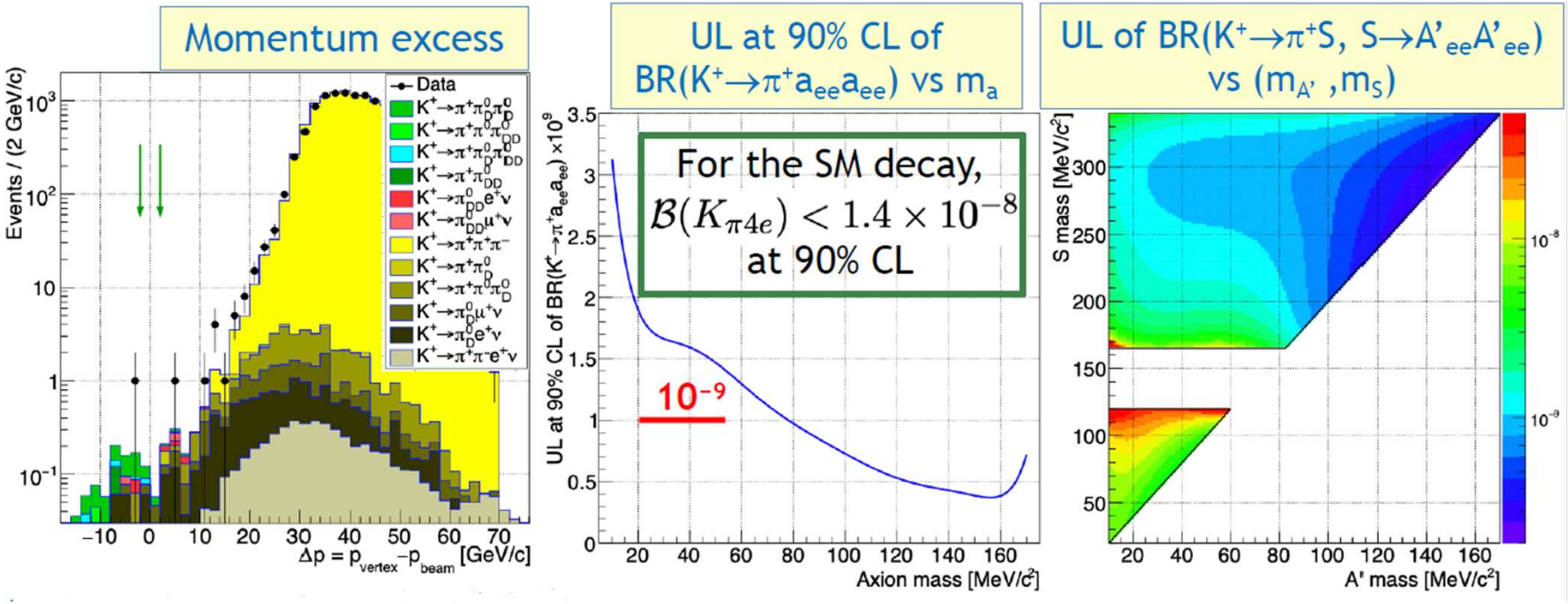
Pair production of BSM particles

NA62 Run 1, multi-electron trigger, five-track selection, $N_K = 8.6 \times 10^{11}$.

3 interpretations:

PLB846 (2023) 138193

- Production and prompt decays of axion pairs, $K^+ \to \pi^+ aa$, $a \to e^+e^-$: exclusion of the QCD axion explanation for the "17 MeV anomaly". Expect $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ for $m_a = 17$ MeV. [Alves, PRD103 (2021) 055018; Hostert and Pospelov, PRD105 (2022) 015017]
- Prompt dark cascade involving a dark scalar (S) and dark photons (A'): $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$
- The SM decay: $BR_{SM}(K^+ \to \pi^+ e^+e^-e^+e^-) = (7.2 \pm 0.7) \times 10^{-11}$ [Husek, PRD106 (2022)]



Beam dump: $A' \to \ell^+\ell^-$

Require ℓ+ℓ− vertex in FV and pointing back to beam interaction point in TAX (CDA vs z)

Background types

Prompt: Interactions of single halo μ with material upstream of/inside FV

Combinatorial: Accidental coincidence of single halo μ

Upstream: Upstream hadrons refocused in the beam-pipe by the GTK achromat

Neutrino induced: Estimated using MC and negligible for all channels

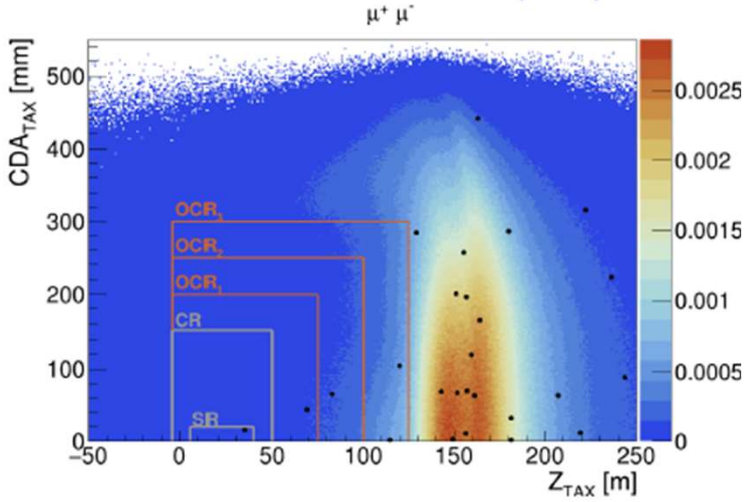
Background estimation

Backwards MC (PUMAS) used to infer kinematics of halo μ

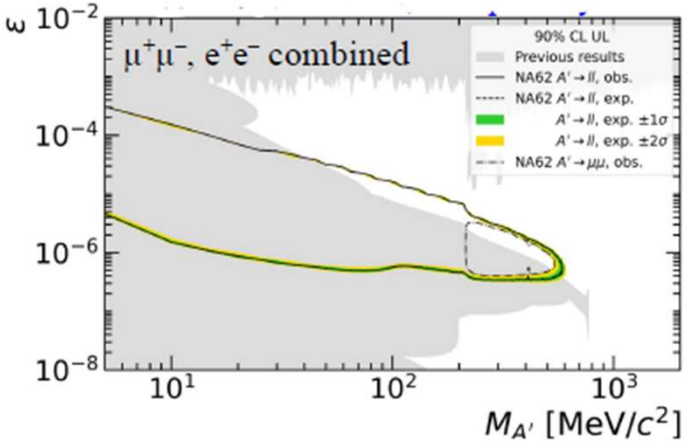
Pair-mixing and forward simulation for background estimate at $O(10^{17})$ POT level

Upstream background estimated by using kaons selected in beam dump data which are used as a gun for the MC simulation

JHEP09 (2023) 035



PRL 133 (2024) 111802



Beam dump: Hadronic final states

Paper in preparation

Production mechanisms considered:

- **Dark photon (DP):** Bremsstrahlung; *V*, *P* decays
- **Dark scalar (DS):** B → K_S decays
- **ALP:** Primakov on/off shell; *P* mixing; B → Ka decays

36 combinations of production and decay channel studied

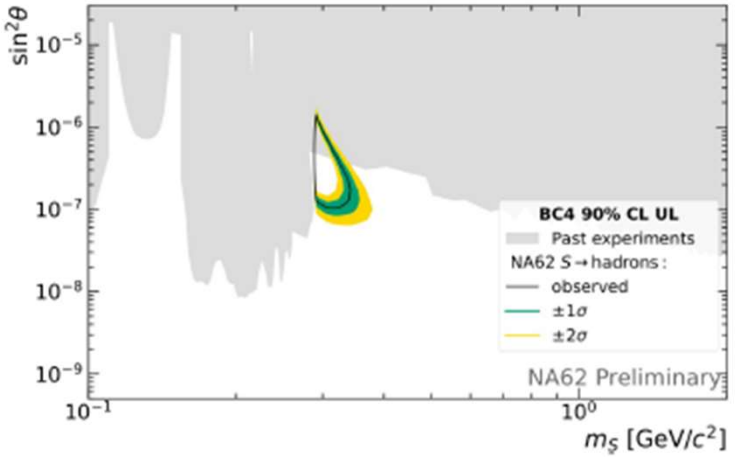
Decay channels studied

DP	DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

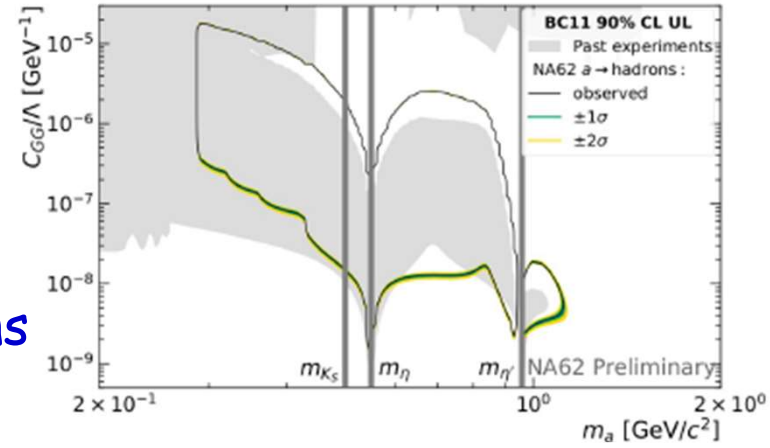
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

0 events observed in all control and signal regions

Higgs-mixed scalar decaying to SM particles (BC4)



ALP with gluon coupling (BC11)



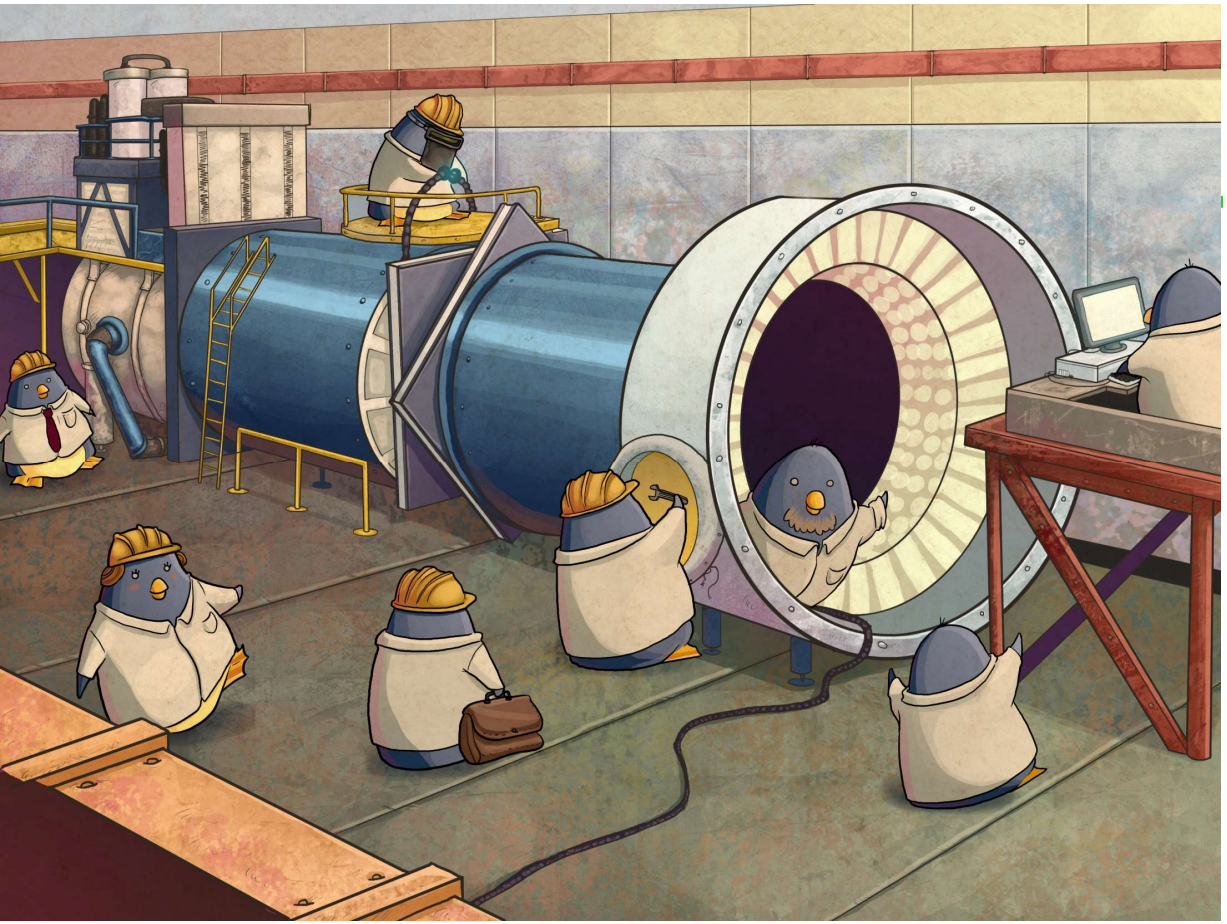
Prospects

- The available results are currently based only on Run1 (2016-2018)
- In the Run2, we expect N_K ~4x
  - Higher intensity
  - Better run conditions
- LNV/LFV decays
  - All presented decays are not background-limited
  - Expected sensitivity 4x (~$1/N_K$)
- Light particle searches
  - not background limited, sensitivity ~$1/N_K$
  - background limited, sensitivity ~$1/\sqrt{N_K}$
- Dump-mode
  - Expected ~10^{18} POT before the end of NA62 (10x increase)
  - 10x better sensitivity for the background free searches

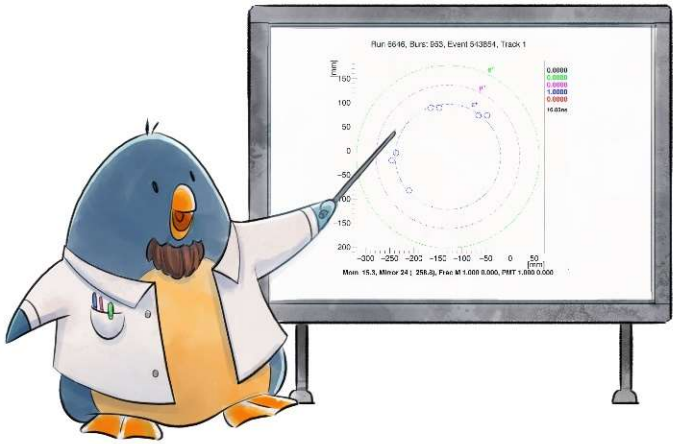
Conclusion

- Besides the main goal of NA62, many searches for new physics have been performed
  - LFV/LNV decay searches with stringent constraints on the BR (~$O(10^{-9}$-$10^{-10})$)
  - Dark sector searches
    - With specific trigger lines and with beam-dump special runs
    - Model-independent limits on the production of dark light particles
    - In beam-dump mode: new results on $A' \to \ell^+\ell^-$ and $X \to$ hadrons

- Prospects
  - Improvements in Run2 on many of the presented analyses
  - 10 times more statistics in beam-dump mode
    - 10^{18} POT expected by the end of NA62



Artist's view of the past installation activity…

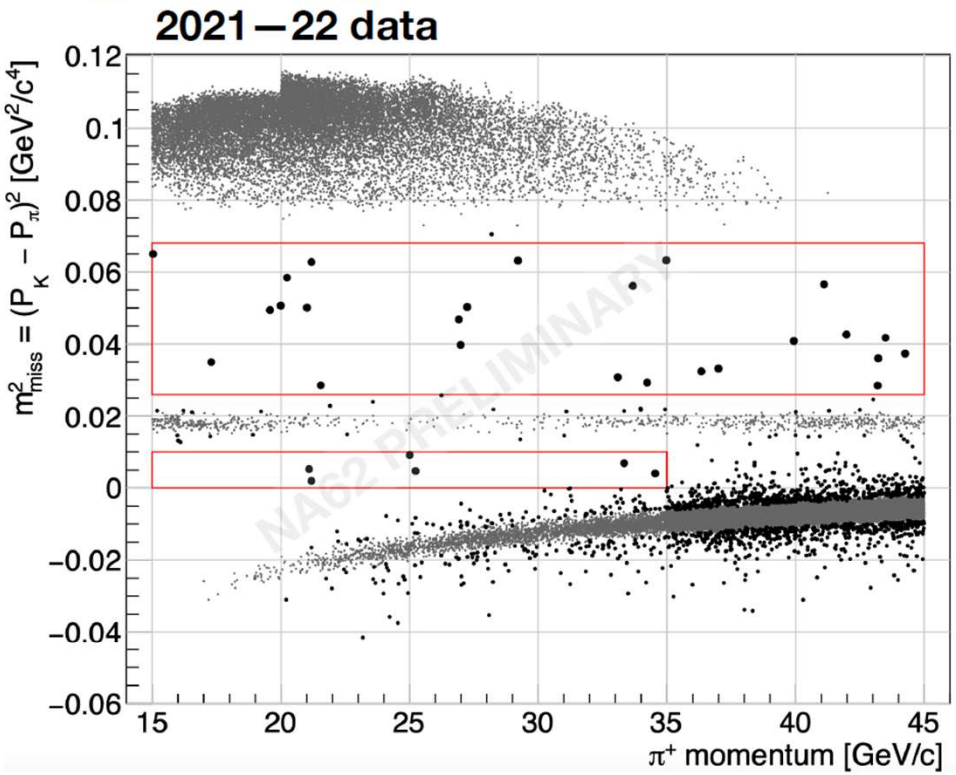


Thank you!

… and of the current analysis work…

Spares

Signal regions

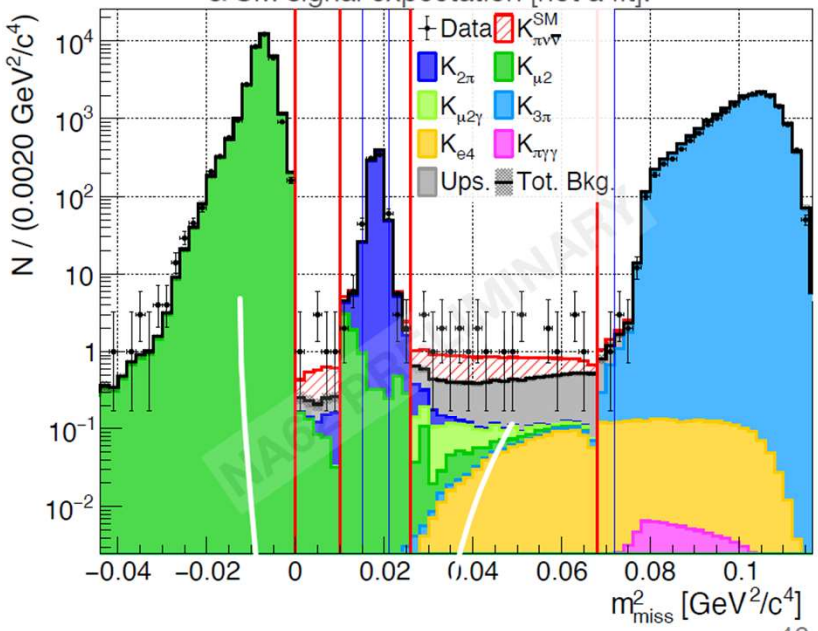


Expected SM signal, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

Expected background, $N_{bg} = 11.0^{+2.1}_{-1.9}$

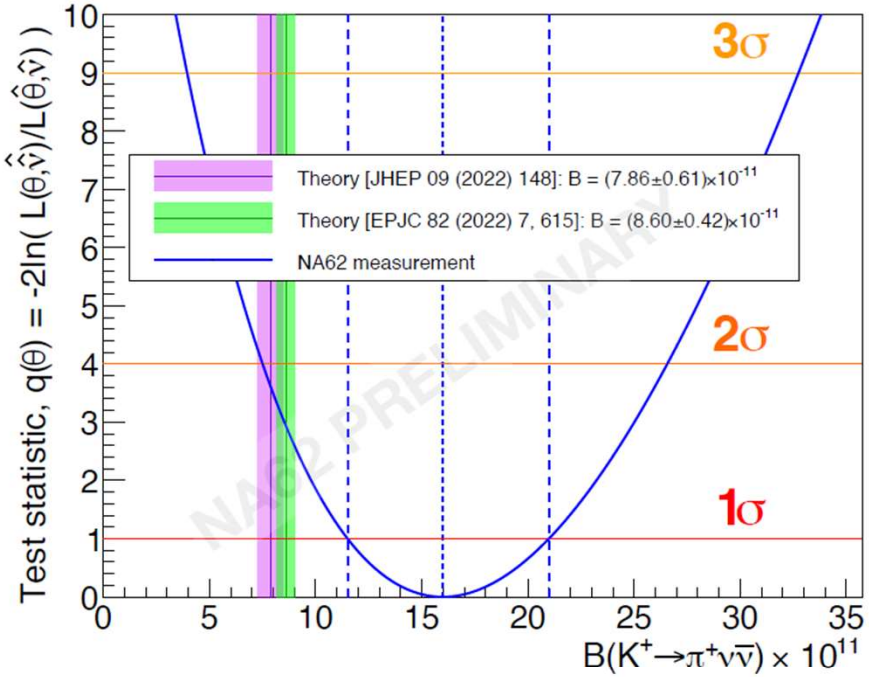
Observed, $N_{obs} = 31$

1D projection with differential background predictions & SM signal expectation [not a fit]:

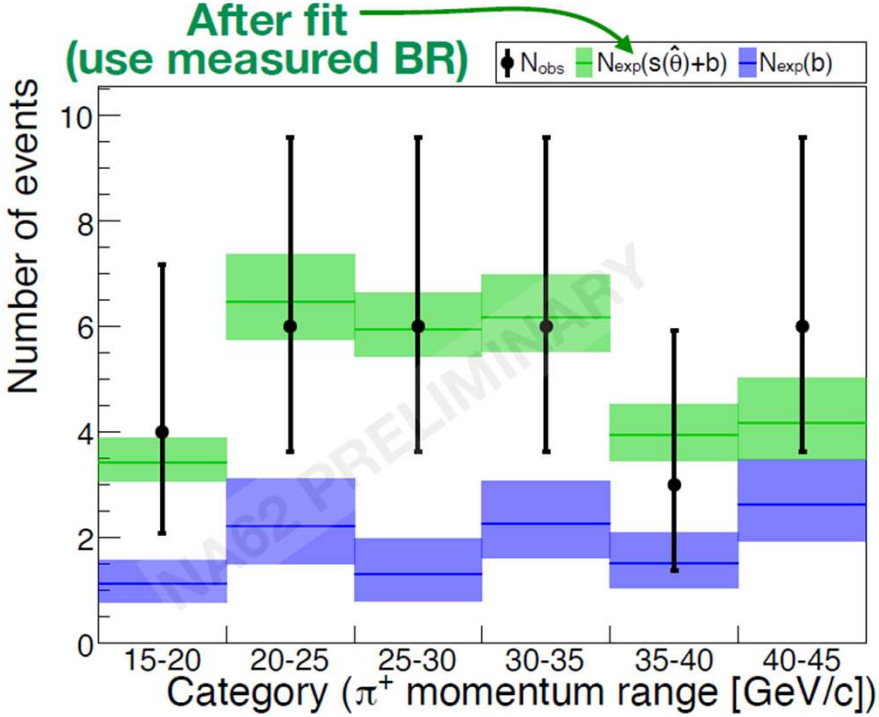


Results: 2021–22 Data

- Measure $\mathcal{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$.



- Use 6 (momentum bin) categories



$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\,(^{+4.8}_{-4.2})_{\text{stat}}\,[^{+1.4}_{-1.3}]_{\text{syst}}\right) \times 10^{-11}$$

Evaluate statistical-only component by repeating procedure assuming exact knowledge of signal and background expectations.

Results in context

BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

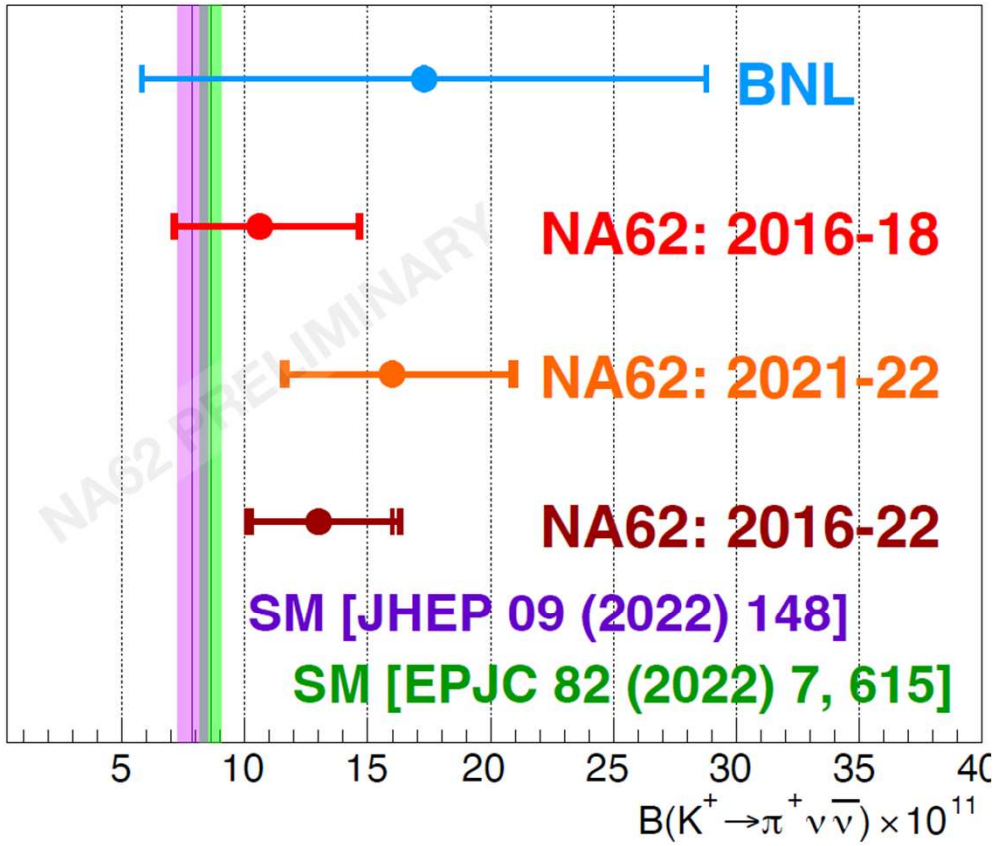
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

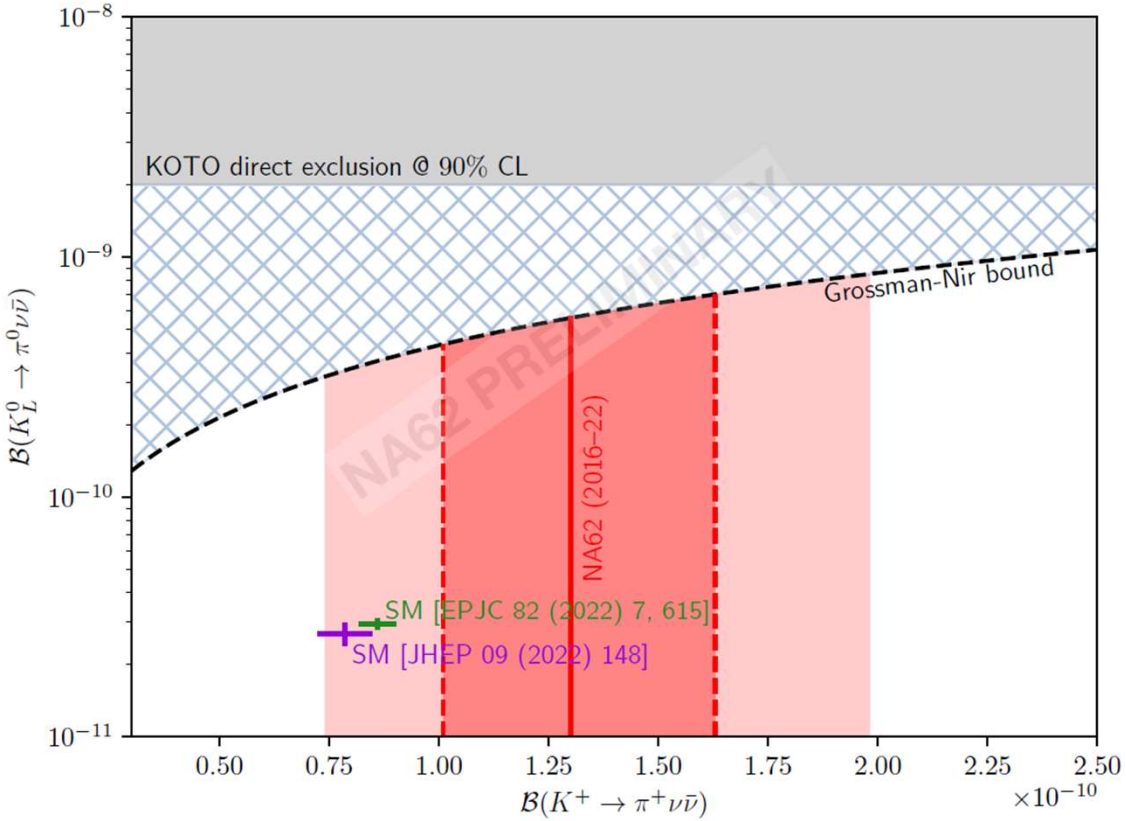
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5–1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5



Results in context

- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance Z>5
- **Observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension**



$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

2σ range : $[7.4 - 19.7] \times 10^{-11}$

KOTO preliminary: [Eur.Phys.J.C 84 (2024) 4, 377]